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Filament-Wound Construction

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A REVIEW OF SELECTED U.S. GOVERNMENT RESEARCH AND DEVELOPMENT REPORTS OTR-140

U. S. DEPARTMENT OF COMMERCE
John T. Connor, Secretary

National Bureau of Standards
A. V. Astin, Director

Institute for Applied Technology
John P. Eberhard, Director

This study is one of a series of reviews of selected Government research and development reports. It highlights significant technical information for the attention of the industrial community. These reports may offer ideas for materials and product development and/or means of reducing production costs.

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A List of the Other Titles in This Series Follows the Bibliographies

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FILAMENT-WOUND CONSTRUCTION

ABSTRACT

Significant reports covering the period since 1962 were selected for this study with reference to earlier works. Recent Government-sponsored research covers such aspects of filament-wound construction as fundamental properties of resins and fibers, methods of producing fibers of various shapes, characteristics of different winding configurations, testing procedures, and applications of filament-wound construction. The reports contain information on the development of theories to explain observed characteristics of resins, filaments, and types of construction as well as listing empirical test results on specific items.

KEY WORDS

Filament-Wound Construction, Glass-Reinforced Plastic, Mandrels, Resins, Pressure Vessels, Laminates, Amines, Winding, Tensile Properties, Composite Materials, Fatigue, Deep-Submergence Vehicles, Hydrostatic Pressure, Creep, Adhesives, Shear Stress, and Binders.

REVIEW OF RESEARCH REPORTS

Resins

An extensive program was recently carried out to determine the correlation between five basic resin parameters and the physical and mechanical properties of resins that might find use in glass-reinforced composites. (See AD–605 179.) Statistical analysis showed that two of the five parameters (viz., type and amount of hardener) have the greatest effect on the 18 physical properties measured. Although the majority of the 18 resin properties were shown to be interdependent, particularly high degrees of interdependency were found between tensile modulus, dynamic shear modulus, heat-distortion temperature, and major glass-transition temperature.

During the second portion of the program, the relationship between the 18 resin properties and horizontal shear strength and burst pressure was investigated. Through the testing of pressure vessels and short span flexural tests of samples from Naval Ordnance-type rings, it was found that the interlaminar

shear strength is apparently related to the tensile strength of the resin and that such properties as tensile strength and elongation have little or no correlation to burst pressure.

The Naval Research Laboratory also believed that agents had a prominent effect upon the properties of plastic binders. In AD–435 479, the investigators report the tensile and elongation properties of several plastics. Each of the plastics contained the same resin—diglycidyl ether of bisphenol-A. The curing agents used during these tests were m-phenylene diamine and two others with similar molecular structures—n-aminobenzylamine and m-xylylene diamine. Because of demonstrated superior elongation and modulus characteristics, the researchers decided to use the m-aminobenzylamine-diglycidyl ether of bisphenol basic plastic system to test internally loaded glass-reinforced filament-wound vessels.

After systematically altering the molecular structure of the amine-cured epoxy resin and then determining the tensile properties, these researchers also found that the tensile properties of the resin had little effect on the ultimate burst strength of the test vessels (AD–609 770). The result showed that, although the resin system has little effect on the ultimate burst pressure, it does have a great effect on the reliability of the burst pressure. That is, a matrix possessing good tensile properties decreases the variations seen from one test vessel to another.

Filaments

Low density, high modulus of elasticity, tensile strength, and flexural strength are necessary characteristics for useful filaments in filament-wound construction materials. In addition, materials that lend themselves to high production rates are required. A screening experiment to find such materials was conducted by the authors of AD–611 757. Using the criterion that the modulus-to-density ratio must be greater than 2.5×10^8 inches, the following materials were selected for study: boron, beryllium, silicon carbide, boron carbide, beryllium oxide, aluminum oxide, titanium boride, and titanium carbide. The production process selected was vapor deposition.

Although the authors found that they could vapor deposit all the materials attempted, the ease with which they could deposit the material and the resulting quality varied considerably for different materials. They also found that the mechanical properties were affected considerably by deposition conditions. In addition to the deposition conditions, crystallinity appeared to have a very strong effect on the achievement of high-strength filaments. Materials that were highly crystalline, such as TiB_2, TiC, Al_2O_3, and Be_2O_3, had low strengths. Those which were amorphous or had very fine crystal structures, such as SiC, B_4C, B, and Be, possessed considerably higher strengths. It was found that SiC, B_4C, B, TiC, and Ti_4B could be deposited at rates which were potentially adaptable to the production of continuous quantities.

A major drawback to circular cross-sectional fibers in filament-wound construction is that theoretically the filaments can be packed only to 90.7% by volume. Since fibers contribute the strength to a composite, it would be advantageous to increase their volume percentage. Different cross-sectional configurations might supply the answer. However, in the past, it has been difficult to manufacture materials of other than circular configuration. Because of the potential value of noncircular fibers, the authors of NASA CR–142 conducted experiments to determine if they could produce hollow filaments in the shape of a square, triangle, or hexagon.

By the end of the program, the investigators had developed a method for drawing a large number of differently shaped glass filaments. This required learning how to control the complex drawing process while dealing with excessive elongation and a substantial cross-sectional reduction. Their work also included resolving the problems presented by surface tension, varying high viscosity, temperature regulation, preform internal pressure, feed rate, and takeup rate.

Although the authors were successful in producing hollow fibers of many different cross-sectional configurations, they point out that there are many problems to be solved before this technique can be commercially adapted. Among these are (1) a comparison of the properties of the filaments made from cemented preforms with those from the same shaped monolithic preforms, (2) the precision winding of shapes other than tapes, and (3) a comparison of properties versus composition.

Prior to the commencement of the program reported in AD–437 124, it had been found that the tensile strength of E–HTS glass-fiber roving was 40% below the published average virgin strength of E-glass fibers (500,000 psi). Because of the importance of these glass fibers to the defense and space programs of the United States, the authors of this publication conducted an experiment to determine where the strength is lost in the manufacturing process. The very extensive investigation, which included 910 measurements of single-fiber strength, 11,000 measurements of strand and roving strength, and 3300 measurements of glass stress in hydrostatically burst, 3–inch-diameter cylinders showed only a 20% loss instead of the previously reported 40%.

The investigators' conclusions were substantiated by the theory that predicts the strength of a bundle of fibers by the strength distribution of the individual fibers in the bundle. This theory was used to analyze the strength-distribution data of several lots of single fibers tested, and it predicted that the tensile strength of a bundle of glass fibers will be 20–25% lower than the average strength of the single fibers.

Another report which concerns itself with the apparent difference between single-fiber strengths and the strengths obtained in filament-wound pressure vessels is AD–439 217. The author stated that several items including flaws, environment, time under load, and the gauge length tested influence the strength differential real or under test. He also pointed out that unequal tensioning limitations due to resin, surface finish, and design factors contribute a great deal to the premature rupture of filament-wound pressure vessels. Perhaps the greatest increase in the strength of glass fibers, and presumably of glass-reinforced plastics, could be obtained by suppressing the effects of ever-present moisture.

The author of AD–439 217 concluded that the bursting strength of single fibers of E-glass should be in the area of one to two million psi, and the authors of AD–405 897 were indeed able to obtain instantaneous strengths of this material approaching the one million psi level by eliminating the effects of moisture. Experimentally, the authors conducted tensile tests at liquid-nitrogen temperature, thus eliminating the effects of humidity. They found that the average fiber strength increased from 507,000 psi at room temperature to 814,000 psi at –196°C. At the lower temperature, 25% of the fibers exceeded 900,000 psi and values as high as 974,000 psi were recorded.

Since it was possible that the temperature alone might have an effect on the tensile strength of the fibers, experiments were conducted whereupon bare fibers were tested submerged in a very powerful desiccant solution, lithium aluminum hydride in ether, at room temperature. The strengths obtained in

this experiment were significantly higher than normal room-temperature strengths, although they were not equal to results obtained at the lower temperatures. The highest value obtained in this portion of the program was 653,000 psi. The authors report that the strength of 500,000 psi recorded for E-glass fibers at room temperature is limited both by the crack structure existing before the test and by a stress-activated corrosion reaction during the test. This latter situation increases the stress concentration at the tips of the cracks and leads to failure at lower loadings.

Until recently, information on the strength of filament-wound structures had been mainly applicable to internally pressurized vessels. However, to develop materials for vessels that operate at great ocean depths, additional information is necessary on filament-wound structures when subjected to high compressive forces. The authors of AD–424 113 believed that it might be advantageous to use larger diameter filaments in structures under compression than those ordinarily used in internally pressurized vessels. To get this hypothesis, they conducted a series of experiments to determine what an optimum diameter might be.

Initial engineering analysis and the subsequent testing of NOL-ring specimens indicated that composite compressive stresses exceeding 30,000 psi could be obtained—a significant advancement over NOL-rings made with conventional glass rovings.

After selecting a 0.005-inch-diameter fiber as the optimum for this particular program, unidirectional and bidirectional cylinders were wound. These were tested under very high hydrostatic external pressures (up to 30,000 psi) and the specimens withstood some very high compressive stresses, which in the case of the unidirectional cylinders approached the ring-specimen values. The highest bidirectional cylinder withstood hoop composite stresses of 182,000 psi—higher than any reported for standard rovings.

Much of the work done in the past on glass-fiber surface treatments has been empirical due to the urgent need for hardware. It has led to many useful commercial treatments, but a more scientific approach is needed for today's space and defense industries. (See AD–426 292) In this publication, the authors discuss many of the theories proposed to explain the mechanism of finishes at the glass-resin interface in reinforced plastics. Evidence for and against the chemical-bonding theory is cited and examined because this is still the only theory that predicts chemical-finish structures that may lead to improved laminate strength.

Testing Procedures

AD–296 094 examines the discussion held in January, 1963, at a special symposium called to review nondestructive tests for filament-wound fiberglass motor cases. Among the various tests discussed were ultrasonics, X-ray, corona discharge, microwave, beta backscatter, spark tests, stati-flux moisture detection, and candling. The author pointed out that a quick-scan technique was needed to cover a whole motor, including insulator. At this time, none was available.

It is very apparent that nondestructive testing (NDT) plays an important part in the manufacture of filament-wound structures. Because of its importance, the authors of AD–602 277 developed a series of experiments that ultimately led to a new ultrasonic testing technique. This NDT technique is able to detect delaminations, unbinding, voids, and resin variations. Other defects with air interfaces, such as crazing and cracks, can also be detected.

However, the authors point out that small amounts of crazing or very fine cracks oriented parallel to the ultrasonic beam may not be detected.

The authors of AD–604 104 had two questions in mind when they started their program. These were (1) what effect would the pressurization rate have on the first-cycle burst pressure of filament-wound vessels?, and (2) what was the effect of pressurization to different levels of proof pressure and humidity exposure on the second cycle of burst pressure of such vessels if pressurized at a very high rate? Experimentally, three types of test specimens were fabricated and tested. These were continuous-filament 8-inch spheroids, cut-filament spheroids, and 4-inch-diameter chambers specifically designed to fail in the hoop windings. These were all fabricated from Owens-Corning's S–994 glass impregnated with Shell 58–68R resin.

Utilizing pressurization rates of 30, 100, and 1,000 psi per second, the experimenters found that the continuous-filament spheroids displayed the greatest strength if they were pressurized at a rate of 100 psi per second on the first-cycle burst test. The burst pressure of the cut-filament spheroids and the 4-inch-diameter chambers also increased in first-cycle tests. However, their increases were very small as a function of pressurization rate. Second-cycle burst tests were conducted only on the continuous-filament spheroids and the cut-filament spheroids. The former show that prepressurization resulted in higher and more uniform second-cycle burst pressure. Prepressurization and humidity exposure had little effect on the cut-filament spheroids.

The Naval Ordnance Laboratory (NOL) has developed what it considers a standard for materials testing (AD–605 681). The method utilizes a mechanical fixture that can be used to determine the compressive properties of NOL-rings. The fixture enables the researcher to collect strength data on filament- or roving-wound rings. The major advantage of this technique is claimed to be the elimination of ring-specimen buckling. Using this method, a tester may apply a maximum composite loading of 300,000 psi on a standard NOL-ring configuration.

The Department of the Army is also exceedingly interested in testing methods for glass-fiber-reinforced plastic materials, particularly for missile cases. Research sponsored by the Department of the Army has developed a unique method of detecting flaws in glass-fiber-laminated plastic materials as small as .0005 inches. The television X-ray imaging system described in AD–433 003 employs small-area Vidicon TV tubes that allow the detection of microscopic imperfections. The image is reproduced on a 17-inch television picture tube with a 32X magnification. This system can be used to scan either stationary or moving materials, and lends itself to high-speed cursory inspection as well as in-depth testing.

The method of nondestructive testing reported in AD–418 330 is acoustical in nature. Initially, this program had two distinct objectives. The first was to develop sound-recording procedures to determine the significance of sounds that emanate from first-state Polaris Model A–3X chambers during hydrostatic testing and to establish the relationship between these sounds and the structural integrity of the chamber. The second part of the program was designed to experimentally determine the velocity of sound in a composite material of fiber filaments and resin, and to determine the effect of filament winding direction and superimposed stress fields on that velocity.

Using accelerometers, the researchers found a significant relationship between the accelerator impulses originating from a filament-wound chamber during hydrostatic testing and the structural integrity of that chamber. The measured acceleration amplitude during the proof-pressure hydrostatic testing

was found to be a function of the chamber burst pressure and inversely related to that pressure. The testing procedure was so successful that the last three burst pressures were predicted with the largest error in these three being 65 psig.

Phase II testings show that the shear velocity of sound is 6% higher in S–994 glass than in E–HTS glass. The data also indicated that in the forward and aft heads of the chamber, the direction of filament winding had no effect on sound velocity. However, in the cylindrical section, the filament winding direction did have a bearing on the velocity.

Deep Submersibles

New technologies are often developed because of necessity; certain final characteristics are needed that are not available. Therefore, empirically, a new method or material is developed which has the required characteristics. This has been true of filament-wound construction. The pattern was followed in the case of externally pressurized vessels such as deep submergent vessels where research has been directed toward the development of materials for this specific application.

The program reported in AD–440 273 had as its purposes the design, fabrication, and testing of small-scale filament-wound models which could withstand a collapsing pressure of 13,333 psi—the pressure at 30,000 feet below the surface of the water. Since this program was directed toward determining potential of composites as a construction material for submersibles, it investigated not only filament-wound plastics but also joining problems such as closures, closure-to-cylinder joints, closure and cylinder penetrations, traverse cylinder joints, and positive frame attachments. The effect of fatigue on penetrations and positive frame attachments was also investigated.

This feasibility study ultimately showed that all the problems mentioned above could be solved. However, the solutions usually resulted in weight/displacement ratio increases over the basic ring-stiffened cylinder. Although the researchers concluded that the use of S-glass proved to be a great improvement in efficiency over E-glass in the closures, another major problem was uncovered during the experiment. The results showed that water will penetrate the wall of a filament-wound composite under cyclic loading, especially when the water contacts cut edges where longitudinal fiber ends are exposed. The researchers pointed out the need for adequate sealing methods to protect the specimen in tests to evaluate the static and fatigue strength of the material.

In an effort to increase the pressures that a filament-wound composite cylinder can withstand, the author of AD–605 963 applied an external coating of synthetic foam to the outside of test cylinders. This foam is composed of epoxy resin filled with microscopic hollow glass spheres. By subjecting composites to external pressures, he found that a great improvement in rupture pressure resistance was obtained—as much as a 160% increase. In addition, he found that while the density of a cylinder was decreased, the buoyancy was increased by a factor of 1.4. This technique increased the stability of the fiberglass filament-wound inner core.

Empirical data is of great importance in a new technology, particularly if one is in great need of hardware. However, to optimize the properties of a new material such as filament-reinforced plastics, one must be able to predict the characteristics of a structure built of this material. With this in mind, the author of AD–433 652 conducted a program to develop and substantiate a

theoretical method for predicting the critical buckling collapse pressure of externally pressurized filament-reinforced cylinders of long, thin-walled monocoque construction. Also, equations capable of predicting significant elastic properties of cylinders were substantiated. Optimum laminate construction was determined, and tests were run on thick-walled cylinders.

Even though filament-wound construction techniques provide the highest strength-to-weight ratios available today, most research on it has been directed to their walls, and major objects such as submarines cannot be made of thin walls. It was deemed advisable to determine design theories, fabrication procedures, and evaluation methods for heavy-walled filament-wound structures that might be practical for submarines and other submersibles. Such a program is described in AD–405 892.

Experimentally, this program was carried out by designing, fabricating, and testing small cylinders and test rings of 29–end E-glass filaments in an epoxy resin. Testing of the cylinders, which ranged from 6 to 18 inches ID and had wall thicknesses up to 4 inches, generally showed that there were no gross changes in the physical and mechanical properties of the laminate due to increasing thickness. However, it was shown that an increase in the maximum circumferential-stress level occurred at each successive change of thickness until a thickness-to-diameter ratio of approximately 0.1 was reached. After this point, failure occurred by material yield or shear at the end plates. Also, the winding pattern was found to be important.

Although most of the cylinders were produced with a ratio of four circumferential plies of roving to each two longitudinal plies, one cylinder that had been wound with a 2:1 ratio showed an increase of 20% in the maximum composite stress. If each succeeding circumferential ply is reversed, (alternately wound in the opposite direction) displacement of the longitudinal filaments after curing could be minimized. Exposure of several test cylinders to 5,000 psi in simulated seawater for up to one month showed less than 5% reduction in the composite stress level and no measurable gain in weight.

In AD–609 708, the author analyzes glass-reinforced plastics for use as construction material for deep-submergence manned vehicles. He compares the composite with materials such as titanium and steel. In addition, he looks at individual characteristics that are extremely important if glass-reinforced plastics are to be used for submersibles. These items include fatigue limitations, shear and tensile cracking, equal tensioning of fibers, layup pattern, and moisture effects. In general, the author concludes that glass-reinforced plastics are feasible construction materials for submersibles, particularly experimental vehicles; and as more engineering information is gathered, much uncertainty about various parameters will be cleared up.

In addition to knowing compressive properties, a knowledge of shear properties is of vital importance in the design of glass-reinforced plastic submersibles. The experiment reported in AD–418 214 was directed toward determining the influence of a number of material variables on the inner laminar shear strength of orthogonal (rectangular) filament-wound materials. When solid filaments were used as reinforcements, failure occurred by shear and at the interface between layers of crossed fibers rather than in a particular layer. In the case of hollow fibers, shear failure occurred in both areas and at values lower than those attained using filaments. Of the three reinforcement materials tested, E–HTS, E–801, and S(994–HTS), the E–HTS laminates produced the highest shear strengths. In addition, little difference was found in shear strength between laminates wound with a 4:2 or a 2:1 dispersion.

In any material contemplated for use as a structural material in deep submersibles, fatigue life is exceedingly important since the vessel will be subjected to differential pressures throughout its lifetime. For this reason, the authors of AD–601 068, under the sponsorship of the Bureau of Ships, conducted a cyclic test on a ring-stiffened, glass-reinforced plastic cylinder. The specimens used in this program were machined from a single thick-walled cylinder fabricated of prepreg E–HTS/E787, 20–end rovings with a resin content of 20 ± 2%. At the conclusion of 8626 cycles, no apparent loss to structural integrity was noted. These samples were subjected to a pressure increase from 200 to 6,700 psi, held for 1 minute at 6,700 psi, after which the pressure was reduced to 200 psi again. After 8626 cycles with no apparent loss of structural integrity, the specimen was loaded to 14,000 psi without catastrophic failure. However, inspection did reveal crazing on the inside surface of the shell in regions corresponding to maximum longitudinal and circumferential stresses.

In every study concerned with deep submersibles, it is important to design not only for resistance to external water pressures, but also for buoyancy so that the submersible can return to the surface. In addition to submersibles, buoyancy is a very important factor in other marine objects such as torpedoes, floats, and buoys. AD–609 821 describes the properties of buoyant materials and structures extensively; among the many applications the authors discuss is that of reinforced plastic for use in rigid shell floats. They compare the potential and properties of reinforced plastics with other materials such as metals; and within the general category of reinforced plastics, they compare the various composites such as glass fiber and epoxy laminates. In addition, they describe properties of various resin systems which can be used with these materials.

Probably the most significant finding reported by the author of AD–603 564 is that by winding fibers in the third planar direction, the apparent interlaminar shear strength of the NOL ring-type specimens under test was increased by approximately 30%. Inconclusive results also indicated that the triplanar winding increased the ultimate compression strength and the fatigue resistance of circumferentially wound cylinders. A comparatively new epoxy resin, (ERLA 0400)[1] used in the screening studies, exhibited interlaminar shear strengths in excess of 15,000 psi.

As part of the Air Force manufacturing methods program, Thiokol Chemical Corporation conducted an extensive investigation into the design, fabrication processes, and equipment required for the manufacture of 65 inch or larger glass-fiber plastic rocket motor cases. The program is reported in AD–602 610 through AD–602 615. Each volume in this series is a technical engineering report on a particular phase of the total program. Program survey, case design and fabrication, and stress analysis are included.

Ultimately, four separate designs were fabricated and hydrotested. Three of the four were monolithic; the fourth (TU–228) was modular. Tests showed that all four were capable of withstanding calculated design pressures; in the case of TU–228 the feasibility of modular construction of glass-fiber cases was adequately demonstrated.

AD–436 272 reports on a 30–month program to produce the optimum filament-wound rocket motor case. Six separate, yet dependent, phases comprised the program. During Phase I, the design and fabrication techniques required to produce the filament-wound pressure vessels were determined. In

[1] Manufactured by Union Carbide Plastics

Phase II, design criteria were validated and data established were suitable for planning and designing future rocket cases. An evaluation of the scaleup factors and the verification of data obtained from model pressure vessels tested in Phase II comprise the third phase. Laboratory and sub-scale case testing to evaluate the physical properties of specific lots of glass rovings was included in the next segment. The evaluation of S–994 glass fiber and the production of a large-scale chamber exposed to axial compression and bending were the last two phases. The successful program produced information on applications in which buckling and stiffness are critical considerations.

A symposium on "Design Criteria for Plastics" was held at Stevens Institute of Technology, Hoboken, New Jersey, in September 1963. One of the papers presented at this gathering was a discussion of problems associated with filament-wound motor cases (AD–425 147). It discussed materials, winding processes, and test processes. Included was a comparison of the engineering properties of various filament-wound composites.

It is an accepted fact that glass-reinforced filament-wound motor chambers are vulnerable to mechanical surface damage. To extend the life and the reliability of chambers that are used for the Polaris A–3, repair procedures had to be developed that could be used at depots. However, before these techniques could be developed, it was necessary to determine the exact effect of surface damage, its size, depth, and location, plus the strength of the motor cases. There are reported in AD–602 632.

Throughout this program, 20–end S–HTS prepreg roving with E–787 resin was used to fabricate 6- and 18-inch-diameter bottles. Wall thicknesses of these specimens were similar to those of the full-scale Polaris A–3 first- and second-stage motor cases. The program demonstrated that the notch-type damage was the most severe. When such damage was to a depth of one or more layers, stress levels well below operational pressure requirements caused the severed hoop windings to peel back. It was also found that an interspersed bottle (wound both longitudinally and circumferentially) was stronger and more resistant to surface damage than a sequentially wound bottle. However, in both types of construction, peeling of the outer windings occurred at low chamber pressures when notched flaws were present.

To correct and repair these flaws, the investigators developed techniques using metal and reinforced-plastic patches that incorporated an elastomeric shear layer. Room-temperature adhesive systems were found to be effective; therefore, an effective depot-type repair technique was developed to arrest peel-back of notched hoop windings.

Much data developed on filament-wound structures are for static condition but ordinarily, structures are subjected to cyclic loading. To determine the effect of load cycling on the failure of an internally pressurized vessel, the program which resulted in AD–422 866 was conducted.

Experimentally, 8-inch-diameter planar-wound isotensoid vessels were utilized throughout the program. These vessels were constructed of rovings of S–994 glass reinforcement impregnated with a resin system composed of Epon 828 [1], Nadic methyl anhydride [2] and dimethylbenzylamine. The vessels were pressurized cyclically within various glass stress ranges and then pressurized at a predetermined rate to the bursting load. The author found that in general, the failure of a vessel under cyclic loading conditions depends on the total time under load regardless of the loading rate, the range of loading, and

[1] Shell Chemical Co.
[2] Allied Chemical Corp.

whether or not the sample had been held at the maximum load intermittently during the cycling. He claims that failure time can be predicted when this total loading time approaches the static fatigue time at the maximum load.

Aerospace Applications

Since filament-wound construction results in very high strength-to-weight ratios one would expect it to have applications useful to the aerospace industry. And so it has. An example is the program reported in N63–19852. To develop a material that could be used in construction of an erectile torroidal space station, this program was directed toward finding a material which possessed not only a high strength-to-weight ratio but one which was also extremely flexible. Among many characteristics that a material appropriate for a space station must possess, the researcher was particularly interested in three. The material must resist repeated thermocycling, function satisfactorily in a high vacuum, and be resistant to electromagnetic and particle radiation.

The leading contender for use in wall construction, the material that possessed all these properties, was found to be natural rubber. It possessed a low initial modulus and high strength at elevated temperatures. Also, the material tended to harden under radiation and resisted the degradation of the space environment. The strength-giving filament was found to be encapsulated glass roving, since it possessed high strength, excellent dimensional stability, resistance to radiation damage, and had suitable folding properties.

Air pressure storage vessels find many uses in high-performance aircraft, especially in emergency functions. Because they perform emergency functions, the storage bottles must be extremely reliable. For this reason, a program was developed to upgrade the lifetime of such bottles to 7 years (2000 flight hours) and to develop vessels that would lose less than 20% of their strength when exposed to high humidity (AD–600 215). For obvious reasons, the program had two limitations:

1. It was necessary that all the materials used in the fabrication of the redesigned pressure vessel be widely available in commercial quantities.
2. All possible improvements should be based on the use of optimum design and processing techniques.

Up to the time of this program, the most outstanding pressure vessels incorporated very thin walls, which could not be used in this particular program. It was decided to determine if thick-walled structures could be fabricated by the multishell concept wherein several thin-walled vessels are wound inside each other, each shell separated from those adjacent to it by a slip plane. At the end of the testing phase of the program, using the best techniques and materials available, the results showed that a lightweight pressure vessel meeting procurement specifications could be built. When weight is not a premium, a vessel could be wound that would meet the weight and space limitations of MIL–T–25363B, and would increase the reliability of the bottle.

An obvious potential use for fiber-reinforced plastics is primary aircraft structures. The question asked in AD–608 439 by the author is, "Why, in light of the many advantages possessed by these materials, are they not now used to fabricate operational aircraft? The major reason," answers the author, "is that the strength properties of these materials are unpredictable and not fully characterized." Along with fiber-reinforced composites, the author has a general discussion of the material, its advantages, and its disadvantages for

aircraft usage. He also discusses today's manufacturing methods, as well as testing problems.

Because liquid hydrogen is of such a low density, storage tanks need to be much larger than those required for other fuels. Particularly in our space program, it is imperative that the weight of these tanks be reduced, and in NASA CR–127, the weight-saving possibilities of filament-wound structures and the built-in insulation properties of these materials are discussed.

The tank designed and built under this program consisted of three main components: a filament-wound glass-fiber shell, an insulating system, and an impermeable liner. The shell, 18 inches in diameter and 36 inches long, consisted of S/HTS 20–end glass roving in a matrix of Union Carbide's No. 2256 epoxy resin and No. ZZL 0820 hardener (a blend of aromatic amine-type hardeners). The insulation consisted of polyurethane foam (density of 4 pounds/foot) encapsulated in a vacuum-tight jacket of aluminum-Mylar-aluminum foil laminate. The impermeable liner consisted of a single laminate and was located inside but not attached to the insulation. The final tank weight, excluding a metal filter tube, was 12.25 pounds. In addition to the process followed to build the tank, basic property data for some of the materials used in the program are presented in the publication. The author concluded that the program's success represented a significant step toward advancing the state of the art of new materials for rocket propellant tanks.

Miscellaneous Programs

The previous descriptions have been classified under various headings; however, there are other worthwhile programs that do not lend themselves to these classifications. These are described in this section.

Since reinforced plastics is a comparatively new class of materials—it has only been about 20 years since they were first used in radomes—much of the data available today is on a short-time basis. However, back in 1953, 20 epoxy- and polyester-laminate samples were set aside to be exposed to a normal laboratory environment. AD–601 591 describes the effect of ten years of exposure on the samples. Comparison of 1963 and 1953 test results shows that simple aging for ten years has had little effect on the flexural strength properties of the laminates produced with the epoxy and polyester resins.

NASA CR–85 is a report on the development of a silver-cadmium battery. However, within the publication is a description of battery cases manufactured by filament-winding techniques. After a series of steps which progressively altered the glass windings and the resin systems, it was finally decided that the battery case would be composed of single-end HTS roving wound with a helix angle of 52°, and to a density of 30 ends per inch. The resin used in conjunction with the glass fiber consisted of 50% Epon 820 and 50% Lancast A. The case walls, which were only 0.010 to 0.020 inches thick, at first were quite permeable and leaked at very low pressures. After the inclusion of a DuPont FEP Teflon film inside the battery case, permeability was reduced to an acceptable level. In addition, the cases were found to be sufficiently strong, lightweight, and were adaptable to the assembly process developed for the battery.

Tests showed that the HTS and selane-finished fibers were poorly met by all the epoxies, regardless of the chemical structure of the liquids or the pressure of amine. Observations at a pilot plant pointed up another major reason for lack of wetting (air entrapment) and the author points out that

even a zero contact angle (perfect wetting action) cannot overcome this problem. Mechanical means must be introduced to solve it.

In AD–602 495, the authors directed their attention toward determining the effect of moisture on the biaxial fatigue and creep properties of glass-reinforced plastics having 20% and 26% resin contents. Among the measurements and experiments performed were density determination, ultrasonic flaw detection, and residual-stress determination.

Results of these investigations illustrated no significant difference in the performance of either material as a function of humidity. Examination of fatigue samples showed that cracking could take place. Creep tests over a 14-month period showed that failures due to this type force were of secondary importance when compared to the fatigue effects.

The authors of N63–11057 have analyzed filamentary structures and developed a theory that should aid design engineers in their use of this type construction material. The report mathematically describes the reactions of filamentary structures when they are subjected to centrifugal loading and pressure. The entire analysis is based upon viewing filamentary structures as monotropic membranes. To substantiate the theory fully, the researchers fabricated and tested models, and found that theory and actual results coincided.

AD–601 581 is an attempt to explain many of the properties of glass-fiber-reinforced plastics through a discussion of surface and polymer chemistry. Using this knowledge, the author also points out ways improvements can be obtained. Among the areas discussed are adhesion of resin to glass, preservation of tensile strength, melting action between resin and glass, and the effect of water on adhesion.

Another document that deals with the surface chemistry of glass-resin composites is AD–604 682. In particular, the author directed his attention to the melting behavior of epoxy resins on glass filaments and its relationship to the fabrication and properties of these composites. Laboratory experimentation was conducted using freshly drawn E-glass filaments, commercial HTS-finished E-glass filaments, and glass fibers coated with hydrolyzedilane finishing agents. Epoxies investigated included an aromatic, a cycloaliphatic, and a fluoroaromatic.

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AD–296 094 U.S. Naval Research Lab., Washington, D.C. REPORT ON SPECIAL MEETING TO DISCUSS NONDESTRUCTIVE TESTS FOR FILAMENT-WOUND FIBERGLASS MOTOR CASES, S. D. Hart, Jan. 63, 7p., CFSTI $1.10.
A discussion of techniques for inspection of fiberglass chambers.

AD–405 892 Aerojet General Corp., Azusa, Calif. STUDY OF THE EFFECTS OF THICKNESS ON THE PROPERTIES OF LAMINATES FOR UNDERWATER PRESSURE VESSELS, R. D. Saunders and R. L. Smith, Mar. 63, CFSTI $2.75.
The basic program was to determine the effects and relationship of thickness on the physical and mechanical properties of filament-wound underwater pressure vessels. Design criteria, fabrication methods, and test methods for thick-walled cylinders were determined by fabricating and testing small cylinders and test rings, and fabrication methods were compared and correlated. An analysis of the fabrication methods and the problems related to thick-walled cylinders is given. Methods of testing and the test results of cylinders and rings are presented.

AD–405 897 General Electric Co., Cincinnati, Ohio. HIGH STRENGTH GLASS FIBERS DEVELOPMENT PROGRAM, D. L. Hollinger et al, May 63, 29p., CFSTI $1.25.
Influence of moisture on the effective strength of E-glass fibers, both as single monofilaments and when incorporated with epoxy resin into filament-wound ring structures, has been investigated. Humidity in the atmosphere surrounding the fiber was controlled during various test periods. Split ring tensile tests on the composites showed a definite advantage for the maintenance of dry surroundings throughout all processing steps. Furthermore, these indicated that the presence of moisture at the time of application of high stress is of much greater significance in determining strength than mere exposure to moisture. By conducting tensile tests at liquid nitrogen temperature (—196°C), the corrosive reaction rate was reduced essentially to zero, with a resulting change in average fiber strength from 507,000 psi at room temperature to 814,000 psi at —196°C. At the low temperature, 25% of the fibers exceeded 900,000 psi and values as high as 974,000 psi were recorded.

AD–418 214 U.S. Naval Applied Science Lab., Brooklyn, N.Y. INVESTIGATION OF EFFECT OF MATERIAL VARIABLES ON SHEAR PROPERTIES OF ORTHOGONAL FILAMENT-WOUND MATERIALS. REINFORCED PLASTICS FOR DEEP SUBMERGENCE AND OTHER HIGH STRENGTH APPLICATIONS, Sept. 63, 11p., CFSTI $1.60.

The influence of a number of material variables on the interlaminar shear strength of orthogonal filament wound materials has been investigated. Included in these studies were different types of reinforcement, reinforcement finishes, methods of winding (wet and prepreg), and fiber dispersions. Materials used are E–HTS, E–801, and S(994–HTS). Data on the tests are given with a complete analysis.

AD–418 330 Aerojet-General Corp., Sacramento, Calif. ACOUSTIC ANALYSIS OF FILAMENT-WOUND POLARIS CHAMBERS, A. T. Green et al, Sept. 63, CFSTI $6.60.

The objectives of this program were (1) to develop sound-recording procedures whereby the significance of sounds emanating from first-stage Polaris Model A3X chambers during hydrostatic testing could be determined and (2) to experimentally determine the velocity of sound in a composite material of glass filaments and resin and the effect of filament-winding direction and superimposed stress fields on that velocity. Both of these test objectives were successfully accomplished. The structural dynamic energy emanating from chambers during hydrostatic pressure tests was recorded by accelerometers and analyzed. Velocity-of-sound measurements were made to determine parameters affecting wave propagation through composite structures. The analysis of recorded data has provided a method for establishing the structural integrity of a chamber after it has been hydrostatically tested to proof pressure. This verification may be made at lower proof pressures than those currently used. Velocity-of-sound measurements have opened other areas of interest that may prove fruitful under further analysis.

AD–422 866 Vermont Univ., Burlington, Vt. THE EFFECT OF REPEATED LOADING ON FILAMENT-WOUND INTERNAL PRESSURE VESSELS, J. O. Outwater, Sept. 63, 18p., CFSTI $1.60.

By subjecting thin filament-wound internal pressure vessels to repeated loads with different rates of loading, load ranges, and duration of peak loads, it is concluded that the principal factor involved in the fatiguing of the vessels is the total duration under load. The life of a vessel under cyclic loading is about the same as might be expected were the vessel to be held at the maximum load until failure through static fatigue. An explanation for this behavior is made qualitatively by examining the acoustical behavior of a vessel under repeated loading.

AD–424 113 NARMCO Industries Inc., San Diego, Calif. OPTIMUM FILAMENT DIAMETERS, B. Levenetz and H. Holland, Oct. 63, 126p., CFSTI $10.50.

Research on E-glass fibers with diameters between 0.001 inches and 0.010 inches was conducted to determine both their physical and mechanical properties and their potential as structural elements in filament-wound circular specimens subjected to external pressure. The effect of fiber diameter on fiber strength, density, modulus, static fatigue, and resistance to seawater has been explored. An engineering analysis was conducted to evaluate analytically the

influence of fiber diameter on composite compressive strength. NOL-ring specimens were wound with various fiber diameters, and it was established by tests that composite compressive stresses exceeding 300,000 psi can be obtained. It was found that the 0.005-inch-diameter fiber combined with a high strength epoxy resin produced in a ring specimen an ultimate composite stress over 300,000 psi. A special process was developed to protect the large diameter fibers from mechanical damage and to control the resin content. Cylindrical unidirectionally and bidirectionally wound specimens demonstrated the strength potential of the large fiber composite by improving the buoyancy efficiency in comparison to standard E-glass roving specimens.

AD–425 147 Picatinny Arsenal, Dover, N.J. FILAMENT WINDING IN MILITARY APPLICATIONS. A DISCUSSION OF PROBLEMS ASSOCIATED WITH FILAMENT-WOUND MOTOR CASES, A. M. Shibley, Sept. 63, 38p., CFSTI $1.00.

Design of filament-wound structures is discussed in relation to material selection, winding technique, quality control, process control, and test methods. The design is illustrated by specific examples of a rocket motor chamber. Buckling is analyzed together with other important engineering properties of the glass filament.

AD–426 292 Naval Ordnance Lab., White Oak, Md. GLASS FIBER SURFACE TREATMENTS: THEORIES AND NAVY RESEARCH, P. W. Erickson, Nov. 63, 26p., CFSTI 75 cents.

This report reviews and discusses the current status of both old and new theories to explain the mechanism of finishes at the glass-resin interface in reinforced plastics. All the evidence for and against the chemical bonding theory is cited and examined in view of the fact that this is still the only theory which predicts chemical finish structures which lead to improved laminate strengths. Both recent and current studies on the resin-glass bond and stronger reinforced plastics are cited and briefly reviewed.

AD–433 003 Ohio State University Research Foundation, Columbus, Ohio. NONDESTRUCTIVE SYSTEM FOR INSPECTION OF FIBER GLASS REINFORCED PLASTIC MISSILE CASES, M. Rhoten et al, Dec. 63, 24p., CFSTI $2.60.

This report describes a unique system for the nondestructive inspection of fiber-glass-laminated plastic missile case materials. This system can produce enlarged X-ray images on a television picture tube with good contrast and detail resolution better than 0.0005-inch. It permits either stationary or in-motion inspection of missile cases. Capabilities of the system are described and representative photographs of images are included.

AD–433 652 Douglas Aircraft Co., Inc., Santa Monica, Calif. OPTIMUM CONSTRUCTION OF REINFORCED PLASTIC CYLINDERS SUBJECTED TO HIGH EXTERNAL PRESSURE, H. R. Jacobson, Mar. 64, 129p., CFSTI $2.75.

This program was to develop and substantiate a theoretical method for predicting the critical buckling collapse pressure of externally pressurized filament reinforced plastic (FRP) cylinders of long, thin-wall monocoque construction. In addition, theoretical equations for the prediction of significant elastic properties of the cylinder were substantiated, the weight efficiencies of

various types of laminate construction or layup patterns were compared, and the optimum laminate construction for monocoque FRP cylinders was determined. Tests were run on thick-wall cylinders of high buckling strength constructions in an attempt to determine biaxial compression strengths of the laminates. Small monocoque cylinders of different types of construction were designed, fabricated, and tested to collapse under external hydrostatic pressure. Very good results were obtained between predicted and measured values of elastic constants, relative buckling strength with variation of hoop and axial ply proportions. Collapse pressure of the buckling test cylinders consistently occurred at higher than predicted values due to greater cylinder end restraint.

AD–435 479 Naval Research Lab., Washington, D.C. FILAMENT-WINDING PLASTICS. PART I. MOLECULAR STRUCTURE AND TENSILE PROPERTIES, J. R. Griffith and F. S. Whisenhunt, Jr., Mar. 64, 5p., CFSTI 50 cents.

An investigation of the liquid resin and curing agents used in the filament-winding process. Two curing agents which are molecularly similar to aromatic diamine curing agents presently used are m-aminobenzylamine and m-xylylene diamine. The first has one aliphatic amino group and the latter has two. The plastic produced from m-aminobenzylamine has outstanding properties and pressure vessels produced using it are believed to be superior to those containing the aromatic diamine presently used. Work is continuing on the program.

AD–436 272 Aerojet-General Corp., Azusa, Calif. IMPROVED FILAMENT-WOUND CONSTRUCTION FOR CYLINDRICAL PRESSURE VESSELS, VOLUME I. STRUCTURAL ANALYSIS AND MATERIALS AND PROCESSES, F. J. Darms et al, Mar. 64, 226p., CFSTI $15.00.

A design-optimization program was conducted which included stress analyses and the determination of design parameters, winding patterns, and fabrication techniques for filament-wound cylindrical pressure vessels. An investigation of the materials, processes, and structural analyses required to efficiently utilize the improved mechanical properties of new glass fibers was also conducted, with the aim of improving the vessels. The selection of various design and fabrication concepts was validated by a series of tests on model and full-scale chambers. The test results indicated that no specific head contour or wrap pattern will yield the highest performance for all variations in dimensional criteria, and that ranges exist in which each design exhibits the better performance. Definite improvement in the composite structure was demonstrated by the use of new glass fibers. Data are provided for use in the design and fabrication of optimum-weight filament-wound cases. Recommendations are presented for additional research.

AD–437 124 Owens-Corning Fiberglass Corp., Toledo, Ohio. GLASS REINFORCEMENTS FOR FILAMENT-WOUND COMPOSITES, E. M. Lindsay and J. C. Hood, Dec. 63, 160p., CFSTI $11.50.

The objective was to investigate the separate steps of the complete glass fiber roving manufacturing process to determine if any portion of a loss in strength difference could be attributed to the manufacturing process and if so, to institute corrective measures. The data indicates a 20% difference between average virgin fiber strength and roving strength. Experiments were run on every step in the process from the bushing through roving, and material was

tested at intermediate points. The results show that the difference between average virgin fiber strength and roving strength in a composite cannot be attributed to any specific process operation. If there is actually a loss in fiber strength, presently available test methods are unable to measure it.

AD–439 217 Naval Research Lab., Washington, D.C. THE STRENGTH OF GLASS FIBERS AND THE FAILURE OF FILAMENT-WOUND PRESSURE VESSELS, J. A. Kies, Feb. 64, 20p., CFSTI 50 cents.

The present day margin of superiority of filament-wound rocket cases over metals on a strength-to-weight basis or a quantitative scale is in a large measure a reflection of the improvement in glass fiber strengths achieved in the past few years. During this time, the production of high-tensile-strength coated fibers designated S-glass or S–994 has been brought under close control. It is shown why the intrinsic strength of the filament as it comes from the bushing does not completely determine the strength of a pressure vessel.

AD–440 273 H. I. Thompson Fiber Glass Co., Gardena, Calif. INVESTIGATION OF STRUCTURAL PROBLEMS WITH FILAMENT-WOUND DEEP SUBMERSIBLES, N. C. Myers et al, Jan. 64, 120p., CFSTI $4.00.

The purpose of this program was to design, fabricate, and test small-scale filament-wound models capable of withstanding a collapse pressure of 13,333 psi (30,000 feet) and a fatigue loading of 10,000 cycles, from O psi to an operating pressure of 6,667 psi (15,000 feet). Problems of major concern were closures, closure attachment, closure and cylinder penetrations, transverse cylinder joints, and positive frame attachments. Material used is epoxy prepreg E–HTS/E787 20–end roving and S–HTS glass prepreg. Methods of analysis, structural studies, strain gage readings and reduction are presented in detail.

AD–600 215 Narmco Industries, Inc., San Diego, Calif. FILAMENT-WOUND PRESSURE VESSELS, F. Wilson, Dec. 63, 103p., CFSTI $9.10.

Air pressure storage vessels are required in high-performance aircraft to perform various emergency functions. Glass filament-wound bottles afford a substantial weight savings over steel and are less subject to fatigue failures because of the stresses imposed on the relatively weak resin binder system. By redesigning the spherical bottle to a cylindrical shape having isotensoid dome ends and by using the multishell method of fabrication, a weight savings of 10% to 15% coupled with an increase in ultimate burst pressure of 15% to 30% was achieved. This redesigning takes advantage of the unidirectional strength characteristics of the glass filament and reduces the stress on the resin binder system to an acceptable level. The method of fabrication to achieve these results incorporated the multishell concept, wherein several thin-walled vessels were wound one inside the other and each shell was separated from those adjacent by a slip plane. Thus, with optimum winding tension scheduling, the composite thick-wall structure could be considered as a thin-walled structure and will exhibit many of the performance characteristics of a thick-wall structure.

AD–601 068 David Taylor Model Basin, Washington, D.C. CYCLIC PRESSURE-LOADING TESTS OF A RING-STIFFENED CYLINDER FABRICATED OF GLASS-FILAMENT REINFORCED PLASTIC, W. P. Couch and K. Hom, May 64, 14p., CFSTI 50 cents.

A cyclic test with a 1-minute hold at a maximum pressure was conducted on a ring-stiffened, glass-reinforced plastic cylinder. The model was subjected to a pressure variation from 200 to 6,700 psi, which corresponds to one-half the collapse pressure of a model with similar geometry under short-term hydrostatic loading. At the conclusion of 8,626 cycles, no apparent loss in structural integrity was noted. The model was then loaded to a hydrostatic pressure of 14,000 psi without catastrophic failure but inspection of the model revealed crazing on the inside surface of the shell in regions corresponding to maximum longitudinal and circumferential stresses.

AD–601 581 Naval Research Lab., Washington, D.C. SURFACE CHEMISTRY OF GLASS-FIBER-REINFORCED PLASTICS, W. A. Zisman, June 64, 13p., CFSTI $1.60.

The report attempts to apply present knowledge of surface chemistry and polymer chemistry to explain many of the properties of glass-fiber-reinforced plastics and to point out ways to obtain improvements. In most respects, the analysis given also applies to any plastic reinforced by a fibrous solid material whose surface is hydrophilic.

AD–601 591 Naval Ordnance Lab., White Oak, Md. LAMINATE STRENGTH CHANGES AFTER TEN-YEARS AGING, P. W. Erickson, Apr. 64, 19p., CFSTI 50 cents.

All laminates were made from style 181 glass fabric treated with many different finishes so as to be compatible with different resin systems. The resins used were Epon 828 and four polyesters (Paraplex P–43, Plaskon 941, Selectron 5003, and Hetron 92). The major finding is that simple aging for ten years has little effect on flexural strength properties of laminates made with epoxy and polyester resins.

AD–602 277 Douglas Aircraft Co., Inc., Santa Monica, Calif. ULTRASONIC TECHNIQUES AND STANDARDS FOR TESTING FILAMENT-WOUND STRUCTURES, C. J. Adams et al, May 64, 100p., CFSTI $2.25.

Optimum techniques and reference standards were developed for ultrasonic testing of filament-wound reference test blocks, 0.1 inch to 2.0 inches thick (in ¼-inch increments), were fabricated. One set of blocks was adhesively bonded to rubber liners that were 0.080 inches to 3.0 inches thick. Ultrasonic tests were performed to measure acoustic properties and to establish optimum test conditions to detect such defects as delaminations, unbond, porosity, and resin content. The tests were performed by immersed through-transmission methods and by both immersed and contact pulse-echo methods. It was found that the optimum method of defect detection was through-transmission methods with facsimile recording. A combination of through-transmission methods and pulse-echo methods was used in evaluating defects detected by through-transmission testing. Pressure vessels of filament-wound structures were ultrasonically tested by these techniques and standards. Discontinuities in these chambers were reliably detected.

AD–602 632 Goodyear Aerospace Corp., Akron, Ohio. STUDY ON THE EFFECTS OF MECHANICAL DAMAGE ON THE PERFORMANCE OF FILAMENT-WOUND MOTOR CASES, R. A. Burkley et al, June 64, 130p., CFSTI $4.00, MF $1.00.

The objectives were to study the effects of surface flaws on the performance of Polaris filament-wound motor cases, to compare the effect of winding

sequence on the ability to resist failure from surface flaws and to determine the feasibility of various repair techniques. Experimental chambers inflicted with notched-type surface damage were tested and evaluated. From these test results, it is shown that the barrel of the chamber is susceptible to peeling of the outermost severed hoop wraps at rather low chamber stress levels. It is also shown that interleaved-type chamber construction is more resistant to surface damage than a sequential construction. However, with both types of chamber construction, peeling of outer windings was found to be a problem. Repair studies were confined to the use of depot-type repair techniques and encompassed the use of metal and reinforced plastic patches incorporating an elastomeric shear layer and bonded with room temperature adhesive systems. This type of repair was able to arrest peel back of notched hoop windings. A detailed description of all aspects of this chamber damage and repair program is presented.

AD–602 495 IIT Research Institute, Chicago, Ill. AN INVESTIGATION OF MATERIAL PARAMETERS INFLUENCING CREEP AND FATIGUE LIFE IN FILAMENT-WOUND LAMINATES, R. H. Cornish et al, May 64, 65p., CFSTI 75 cents.

Results are given of a program to study the environmental (wet vs. dry) effects on the biaxial fatigue and creep (stress-rupture) performance of glass-reinforced plastics having 20 and 26% resin contents. Characterization of the materials studied in regard to resin content and density determination, ultrasonic flaw detection, and residual stress are included. Correlation of ultrasonic flaw scan patterns with sites of principle failure is made. Residual strain measurements on ring specimens using both "peel" and "cut coupon" techniques are shown to indicate residual tensile stress on the inside surface of the ring and residual compression on the outside. The results indicate no significant difference in performance of either of the materials considered for the wet and dry test environments used. Microscopic inspection of cross-sections from runout fatigue experiments show that significant cracking may develop at any point in the cross-section and does not appear to be a function of the test environment. Stress rupture experiments to date show that excessive deformation and failure due to sustained stresses is of secondary importance when compared to the more severe fatigue effects.

AD–602 610 Thiokol Chemical Corp., Brigham City, Utah. REINFORCED PLASTIC CONSTRUCTION METHODS FOR LARGE ROCKET MOTOR CASE. VOLUME I. PROGRAM SURVEY, W. G. Morse and F. W. Dallon, Dec. 63, 272p., CFSTI $6.00, MF $1.50.

The objective of the program was the development of designs, fabrication processes, techniques and equipment for manufacture of fiberglass plastic rocket motor cases. Case designs and manufacturing methods were established for both monolithic and modular construction of large plastic cases. Design included derivation of dome contours, stress analysis of case assemblies and components, and specification of fiberglass, resin systems, case liners, hardware, and mandrels. Two cases of each design were fabricated, at least one of which was subjected to hydroburst testing. Hydroburst tests on small diameter cases (18 inches in diameter) proved the feasibility of modular construction of fiberglass cases. 44-inch diameter cases withstood design pressure (794 psig design; 1185 and 1188 psig burst) with high stress (300,000 psi). A large case (65 inches in diameter) ruptured below the design proof

value (890 psig design; 840 psig burst). Failure was attributed to module misalignment rather than to design defect.

AD–602 611 Thiokol Chemical Corp., Brigham City, Utah. REINFORCED PLASTIC CONSTRUCTION METHODS FOR LARGE ROCKET MOTOR CASE. VOLUME II. CASE DESIGN AND FABRICATION, W. G. Morse and F. W. Dallon, Dec. 63, 327p., CFSTI $7.00, MF $1.50.

From specifications and drawings, case designs and fabrication processes were established for TU–226A, TU–226B, TU–227A, and TU–227B monolithic fiberglass reinforced plastic cases. These cases were designed and fabricated to develop manufacturing methods for large (65 in. diameter or larger) plastic rocket motor cases. Case design included derivation of dome contours, analysis of dome, case cylinder, and skirt stresses, determination of component weights, and specification of glass filament size, resin system, case liner material, hardware, and case mandrels. Winding patterns and wrapping angles were evaluated by computer program for specific applications. Two cases of each design were fabricated, and at least one case of each design was subjected to hydroburst testing. The TU–226A (Lamtex) case withstood design pressure (1113 psig design; 1164 burst). The TU–227A (Allison) case also withstood design burst pressure (792 psig design; 1185 psig burst). Failures due to causes other than case rupture (forward skirt failure; aft cover plate failure) prevented attainment of case rupture for other cases. (Author)

AD–602 612 Thiokol Chemical Corp., Brigham City, Utah. REINFORCED PLASTIC CONSTRUCTION METHODS FOR LARGE ROCKET MOTOR CASE. VOLUME III. TU–228 CASE DESIGN AND FABRICATION, W. G. Morse and F. W. Dallon. Dec. 63, 129p., CFSTI $4.00, MF $1.50.

From specifications and drawings, the case design and fabrication processes were established for a modular construction of fiberglass plastic cases. These cases were designed and fabricated to develop manufacturing methods for large (65 in. diameter or larger) plastic rocket motor cases. Cases design included derivation of dome contours; analysis of dome, case cylinder, and skirt stresses; determination of component weights; and specification of glass filament size, resin system, case liner material, hardware, and case mandrels. Winding patterns and wrapping angles were evaluated by computer program for specific applications. Two small cases and one large case were fabricated and subjected to hydroburst testing. The design feasibility and fabrication techniques were successfully proven in subscale tests, in which the cases burst at 143 and 162 percent of the design ultimate pressure. While the larger case burst below design limit (proof) pressure (840 psi burst; 890 psi design), sufficient data, recorded from case behavior under pressure and from analysis of the mode of failure, permitted complete evaluation of the modular design. The stiffness of larger modules introduces deviations which affect case strength and performance under test. (Author)

AD–602 613 Thiokol Chemical Corp., Brigham City, Utah. REINFORCED PLASTIC CONSTRUCTION METHODS FOR LARGE ROCKET MOTOR CASE. VOLUME IV. TU–290 CASE DESIGN AND FABRICATION, W. G. Morse and F. W. Dallon, Dec. 63, 134p., CFSTI $4.00, MF $1.00.

From specifications and drawings, case designs and fabrication processes were established for the TU–290 monolithic fiberglass case. Phase III program requirements specified development, by progressive improvement of case de-

sign following fabrication, hydroburst, and evaluation, of a single nozzle case; a case to have a motor mass fraction (excluding igniter) of 0.965, and which could withstand 400,000 psi hoop stress at a burst pressure of 792 psig. The first three (of five) cases were hydroburst to evaluate designs, materials, winding equipment, and fabrication techniques. These cases withstood 575, 660, and 750 psig, respectively. The results for case No. 3 (379,000 psi hoop stress at 750 psig) were considered to satisfy design aims and objectives (Supplemental Agreement No. 5, dated 6 June 1963). The remaining two cases, fabricated with insulation, successfully withstood hydroproof testing at 550 psig. For subsequent tests on these cases, motor and nozzle designs were prepared. A single, recessed, fixed, conical nozzle was fabricated and delivered to the Air Force for each of the two cases. (Author)

AD–602 614 Thiokol Chemical Corp., Brigham City, Utah. REINFORCED PLASTIC CONSTRUCTION METHODS FOR LARGE ROCKET MOTOR CASE. VOLUME V. MANDRELS, W. G. Morse and F. W. Dallon, Dec. 63, 101p., CFSTI $4.00, MF 75 cents.

Mandrels have been developed during this program for rocket motor use in R and D or in production programs. The mandrel design must be selected to accent flexibility of tooling for changes in case design, to accent durability in repeated use, or for economy in case production. Mandrel cost, weight, performance, and reliability must also be considered. A plaster or a plaster-shell-over-plywood construction readily permits changes in dome contours or case wall diameters. A cast mandrel of sand and resin, or a mandrel having extruded aluminum segments, required a low capital outlay and permits high case production rates if the case configuration is fixed. The sand-resin mandrel is relatively heavy among the five designs used. The dimensional stability and the light weight of the extruded mandrel are positive assets for fabrication of fiberglass cases larger than 60 in. dia but certain factors are not clearly defined (the reliability of its unique pressurization system and the potentially variable tension on glass fibers wound over aluminum). (Author)

AD–602 615 Thiokol Chemical Corp., Brigham City, Utah. REINFORCED PLASTIC CONSTRUCTION METHODS FOR LARGE ROCKET MOTOR CASE. VOLUME VI. STRESS ANALYSIS, W. G. Morse and F. W. Dallon, Dec. 63, 259p., CFSTI $6.00, MF $1.50.

A detailed stress analysis was completed for each case design. Emprical equations for basic cylinder, dome, skirt, blast tube reinforcements, and metal parts design were derived, together with general equations for stability (buckling under load) and discontinuity analysis. Specific evaluation of each case design for these considerations was completed, together with an analysis of design deviation from general conditions, or analysis of redesigned portions where appropriate. Following the analysis, each case design was established as capable of withstanding all stresses imposed under normal flight sequence.

AD–603 564 Whittaker Corp., San Diego, Calif. INTERLAMINAR SHEAR OF FILAMENT-WOUND REINFORCED PLASTICS, R. A. Elkin, July 64, 49p., CFSTI $2.00, MF 50 cents.

This program was conducted in an effort to improve the interlaminar properties of filament-wound structures. One of the newer epoxy resins (ERLA 0400) used in the screening studies exhibited interlaminar shear strengths in excess of 15,000 psi. By winding fibers in the third planar direction, the

apparent interlaminar shear strength of the NOL ring type specimens was increased by approximately 30%. Although the test data were not completely conclusive, results indicated that the triplanar winding increases both the ultimate compression strength and fatigue resistance of circumferentially wound cylinders.

AD–604 104 Aerojet-General Corp., Sacramento, Calif. HYDROSTATIC TEST PROCEDURES, July 64, 40p., CFSTI $2.00, MF 50 cents.

The results obtained in hydrostatic tests of continuous-filament spheroids, cut-filament spheroids, and 4-inch diameter chambers designed to fail in the hoop windings, were presented. The spheroids were burst either on the first cycle at one of three pressurization rates or on the second cycle after exposure to various environmental conditions. The 4-inch diameter chambers were divided in three lots, pressurized at one of three pressurization rates, and burst on the first cycle. The effect of these various hydrostatic test parameters on burst pressure were evaluated.

AD–604 682 Naval Research Lab., Washington, D.C. SOME SURFACE CHEMICAL ASPECTS OF GLASS-RESIN COMPOSITES. PART I. WETTING BEHAVIOR OF EPOXY RESINS ON GLASS FILAMENTS, W. D. Bascom, Aug. 64, 25p., CFSTI 50 cents, MF 50 cents.

A study is made of the wetting behavior of epoxy resins on glass filaments and its relation to the fabrication and properties of filament-wound glass-resin composites. Three different types of epoxy liquids were used: an aromatic, a cycloaliphatic, and a fluoroaromatic, with and without the addition of amine curing agents. Attempts to improve wettability by adding fluoroorganic surfactants to the epoxy liquids were unsuccessful. It was concluded that for optimum impregnation, it is necessary that the resin wet the glass fiber at a zero contact angle and, since this condition alone will not eliminate air entrapment, mechanical means must be provided in the winding operation to minimize it and to release air bubbles from the roving.

AD–605 179 Aerojet-General Corp., Sacramento, Calif. DEVELOPMENT OF IMPROVED RESIN SYSTEMS FOR FILAMENT-WOUND STRUCTURES, J. J. Cooney, Aug. 64, 330p., CFSTI $7.00, MF $1.50.

The report showed by regression equations and charts of response surfaces the relationships between five resin system parameters and 18 physical properties of the resins. The results were based on 31 experiments arranged in a central composite design for each of seven hardeners. Statistical techniques were used for designing the experiments and interpreting the results. The results indicate that the type and amount of hardener used are the most important of the parameters studied in effecting changes of properties, especially for those resin systems that contain amine hardeners. The relationships that exist between the physical properties of the resins and those of a filament-wound composite were investigated through the fabrication and bursting of 70 pressure vessels and short-span flexural tests of samples from 140 rings for interlaminar shear-strength determinations. Correlation analysis has shown the majority of the 18 resin properties to be interdependent.

AD–605 681 Naval Ordnance Lab., White Oak, Md. A METHOD OF TEST FOR DETERMINING THE COMPRESSIVE PROPERTIES OF FILAMENT-WOUND NOL-RINGS, S. P. Prosen, July 64, 30p., CFSTI $2.00, MF 50 cents.

A mechanical fixture was developed to determine the compressive properties of NOL-rings and to enable the researcher to collect strength data on filament or roving wound rings. This data was important in the development of external pressure vessels. The tester can apply a maximum composite loading of 300,000 psi on a standard NOL-ring configuration. The author recommends that the method of testing be adopted as a standard for the determination of uniaxial compressive properties of filament-wound structures utilizing the NOL-ring specimens.

AD–605 963 GM Defense Research Labs., Santa Barbara, Calif. SYNTACTIC-FOAM, FILAMENT-WOUND COMPOSITE PRESSURE HULLS, R. M. Robertson, Sept. 64, 75p., CFSTI $3.00, MF 75 cents.

This report describes the design and testing of composite cylinders that have an inner core of fiberglass filament windings and an external coating of syntactic foam. The syntactic foam is a matrix of epoxy resin and microscopic hollow glass spheres. All test specimens were subjected to external hydrostatic pressure to the point of rupture so that comparisons could be made of (1) rupture pressures, (2) material densities, (3) buoyancies, and (4) thicknesses of syntactic foam. Results indicated that by coating the cylinders with a layer of syntactic foam, the unit was stabilized in the buckling mode, and a great increase in strength was achieved before rupture from externally applied hydrostatic pressure. Also, the buoyancy of the composite structure was significantly increased.

AD–608 439 Wright-Patterson AFB, Ohio. PHILOSOPHY FOR THE DESIGN OF PRIMARY AIRCRAFT STRUCTURES WITH FIBROUS REINFORCED COMPOSITES, R. L. McGuire, Jr., Nov. 64, 17p., CFSTI $1.00, MF 50 cents.

Emphasis is on a possible approach to establishing useable design philosophies for utilizing FRC for major airframe components. The general nature of these materials is outlined, with accompanying thoughts for assessing the material characteristics. Advantages and disadvantages were listed, with more emphasis on areas of needed research. An attempt was made to associate these research areas with the appropriate technical field of interest.

AD–609 708 Naval Research Lab., Washington, D.C. A NAVY ANALYSIS OF GLASS-REINFORCED PLASTICS FOR HYDROSPACE APPLICATIONS, J. A. Kies, Nov. 64, 39p., CFSTI $2.00, MF 50 cents.

Recent advances and remaining problems in the study of filament-wound glass-reinforced plastics were reviewed. Areas considered were fatigue studies, shear and tensile cracking, equal tensioning of fibers, part reinforcement, layup patterns, moisture effects, fiber properties, mechanical damage, and effects of porosity or bubbles in the resin. Emphasis was given to application to shells for manned deep submergence vehicles.

AD–609 770 Naval Research Lab., Washington, D.C. FILAMENT-WINDING PLASTICS. PART 2. ROLE OF THE RESIN IN GLASS-FIBER-REINFORCED STRUCTURES UNDER TENSILE STRESS, F. S. Whisenhunt, Jr., Dec. 64, 18p., CFSTI 50 cents, MF 50 cents.

This report is a continuation of AD–435 479. It covers a series of experiments to determine how resins contribute to the ultimate burst strength of filament-wound motor cases. The approach was to make an orderly change in the chemical structure of the curing agent of the plastic matrix in order to

create different mechanical properties. A study was conducted on amine-cured epoxy resins and the effects on the ultimate burst strength of internally loaded glass-reinforced filament-wound vessels when these resins were used as the plastic matrices. It was found that resin tensile properties had an insignificant effect on the ultimate burst strength of a well-designed and well-fabricated vessel. The glass stresses at burst of the test vessels were in the 400,000 psi range, which is about the ultimate tensile strength of bundles of E-glass.

AD–609 821 Proteus, Inc., Whippany, N.J. PROPERTIES OF BUOYANT MATERIALS AND STRUCTURES, J. Irgon et al, Aug. 64, 254p., CFSTI $6.00, MF $1.50.

This report was directed at furnishing information on the various kinds of materials which can be employed for the construction of flotation devices, a description of typical float structures comprised of the materials listed, and generalized mathematical relations for calculating the buoyancy and related parameters of a structure in any form and combination of materials. The data are restricted to properties that are most frequently employed in design and analytical studies and for which reasonable reliable values can be obtained.

AD–611 757 General Technologies Corp., Alexandria, Va. A STUDY OF HIGH MODULUS, HIGH STRENGTH FILAMENT MATERIALS BY DEPOSITION TECHNIQUES, L. G. Davies et al, Jan. 65, 39p., CFSTI $2.00, MF 50 cents.

The primary purpose was to determine the feasibility of vapor depositing certain candidate materials in filament form to yield high strength, lightweight reinforcement materials. The materials selected were boron carbide, silicon carbide, boron, titanium boride, titanium carbide, beryllium, beryllium oxide, and aluminum oxide. All were successfully deposited. The boron carbide, silicon carbide, and boron deposition reactions produced high quality coatings at reasonable deposition rates. The others produced filaments of generally lower strengths. The best filaments produced by each process were evaluated by measuring the tensile strength, modulus, and density. A secondary objective was to appraise the ease of deposition and adaptability to the production of continuous lengths. It was found that the structure and, therefore, the strength was quite sensitive to the deposition parameters.

NASA CR–85 Telecomputing Corp., Denver Colo. SILVER-CADMIUM BATTERY DEVELOPMENT PROGRAM, J. M. Rice, Sept. 64, 211p., CFSTI $3.50.

The development of a lightweight, silver-cadmium secondary battery for space applications was described. The battery case was filament-wound, using glass fiber reinforcement. A complete description was given of the plastics material selected, type of tests, and results.

NASA CR–127 Goodyear Aerospace Corp., Akron, Ohio. DESIGN AND FABRICATION OF AN INTERNALLY INSULATED FILAMENT-WOUND LIQUID HYDROGEN PROPELLANT TANK, C. B. Shriver, Nov. 64, 61p., CFSTI $1.75, MF 75 cents.

The program objectives were to develop and fabricate a lightweight liquid propellant tank consisting of three main components: filament-wound fiber-

glass shell, insulation system, and an impermeable liner. The fiberglass shell was cylindrical with dome ends, 18 inches in diameter by 36 inches in length with a design maximum test pressure of 100 psi. The shell consisted of S/HTS 20–end glass roving in a matrix composed of epoxy resin and hardener. Insulation was located internally and consisted of polyurethane foam encapsulated in a vacuum-tight jacket of aluminum-Mylar-aluminum foil laminate. The liner consisted of a similar laminate located inside but not attached to the insulation. The tank weight was 12¼ pounds. Subsequent tests indicated that this type of tank for liquid hydrogen use can be successfully fabricated.

NASA CR–142 DeBell and Richardson, Inc., Hazardville, Conn. STUDIES OF HOLLOW MULTIPARTITIONED CERAMIC STRUCTURES, W. J. Eakins and R. A. Humphrey, Dec. 64, 67p., CFSTI $3.00.

Results were presented of forming glass filaments whose shape was other than a solid round. The feasibility of drawing precise geometric shapes of fibers was demonstrated. With the objectives of high stiffness-to-weight ratio, most of the fibers were drawn into hollow cross-sections of various shapes for filament winding. Complex hollow fibers can also be drawn by the highly refined preform attenuation process used in this program.

N63–11057 Astro Research Corp., Santa Barbara, Calif. A THEORY AND APPLICATIONS OF FILAMENTARY STRUCTURES, H. U. Schuerch et al, Dec. 62, 83p., CFSTI $2.25.

This report dealt with a specific and relatively important species of filamentary structures—namely, those produced by filament-winding processes, both from the point of view of developing a basic understanding, and applications to toroidal pressure containers. A theory of filamentary structure consisting of monotropic membranes was presented. Applications to isotensoid pressure vessels with rotational symmetry demonstrated the use of the theory. Particular attention was given to applications of filamentary design of variable-geometry expandable structures. Physical interpretation of the resulting shapes and winding patterns lead to a discussion of the morphology of filament-wound pressure vessels. Experimental data, obtained from filament-wound toroidal pressure vessels, confirmed the validity of the theory and demonstrated application of the analytical design technique for filamentary structures.

N63–19852 U.S. Rubber Co., Wayne, N.J. A RESEARCH STUDY TO INVESTIGATE THE APPLICATION OF FILAMENT WINDING FOR SECTIONS OF AN ERECTABLE SPACE STATION, M. W. Olson, Apr. 63, 44p., CFSTI $3.00, MF 50 cents.

The program consisted of screening available materials and establishing fabricating practices which would result in the most desirable filament-wound structure for the application. High strength-to-weight with flexibility was desired, with reliability and compatibility with the space environment. Cords exhibiting considerable promise as the tensoidal element comprised (a) encapsulated glass roving, and (b) a high tenacity filament steel wire. The preferred binder material consisted of compounded natural rubber, polyurethane, and ethylene propylene rubber. Materials best suited for elevated and depressed temperature environments were described. The investigation included the test results and a list of suggested future studies.

EARLIER BIBLIOGRAPHY—FINAL REPORTS ONLY (1959-1964)

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AD–405 551 H. I. Thompson Fiber Glass Co., Gardena, Calif. INVESTIGATION OF STRUCTURAL PROBLEMS WITH FILAMENT-WOUND DEEP SUBMERSIBLES, N. Myers and G. Lee, Apr. 63, 124p., CFSTI $4.00.

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AD–427 009 IIT Research Inst., Chicago, Ill. AN INVESTIGATION OF MATERIAL PARAMETERS INFLUENCING CREEP AND FATIGUE LIFE IN FILAMENT-WOUND LAMINATES, R. H. Cornish et al, Dec. 63, 10p., CFSTI $1.60.

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